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STATE OF TUNING

Shigenori Okubo

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16. Abstract

The trend of today's tuning is changing from the off-line type of Ziegler-Nichols to the on-line, however, we are still far away from complete auto-tuning. This article discusses some of the aspects of tuning.

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STATE OF TUNING

Shigenori Okubo**

1. Introduction

The problem of tuning is old, but there is a new theme. Although the method by Ziegler and Nichols [21] was proposed in the 1940s, the PID control is the most popular control method for practical use. The operation for step response and self-excited oscillation was possible in cases where the controlled system was comparatively small scale. The controlled system of the present time is large scale; thus large amounts of cost and time consumption are required for such an operation. Therefore, operation of the Ziegler-Nichols method is rare at present. After all, the tuning of the parameter is dependent on the ability of expert operators who have mature experience and knowledge. The expert operators observe the motion of the measured signals and if they fall outside of the judgement boundary, the operators correct the parameter and continue the monitoring and by repeating this operation, the optimum parameter is converged within. It is not an exaggeration to say that the above is the status at present. When the controlled system becomes large scale and complex, obtaining accurate identification is difficult. Making accurate model complying changes of the outer environment obstructs the operation and it causes a decrease in manufacturing efficiency. Thus, it is desired that identification can be done from the operation signal only but in general, the identification signal has to be PE (persistently exciting) so the problem is a difficult one. Because of the above reasons, an ironic phenomenon occurred in which the automatic control apparatus which directs other apparatus automation is itself most automated. With the advance of computers in recent years, there is a trend toward a method using engineering knowledge and artificial intelligence for parameter tuning.

*Numbers in margin indicate pagination of foreign text.

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It aims at replacement of the judgement of expert operators with computer systems, i.e., it is an application of the expert system and it seems that this trend is becoming more pronounced.

The tuning method described in this report does not cover everything but the author hopes that this report helps the reader to understand present trends.

This report shows that the tuning method is developed as an instrumentation control system and the auto-tuning apparatus of the system is described in paragraph 2. In paragraph 3, the unique tuning method which uses the characteristics of the controlled system, but not as the instrumentation system, is described. In paragraph 4, the tuning algorithm which is used in many present applications is described.

2. Auto-tuning apparatus

2.1 Expert self-tuning controller

Here, the electronic instrumentation control system, new YEWSERIES 80 of Yokohama Hokushin Electric Co., is introduced. Following the YEWSERIES 80 (written as YS-80 for short) of the first generation, the new YEWSERIES 80 (written as NYS-80) was developed as a more powerful product. The main strong point of NYS-80 is that its functional integration is improved as well as the expert system of the AI (artificial intelligence). This most advanced computer software was made practicable by means of optimal parameter inference of the PID control. It may appear that a combination of the most classic PID control and the most advanced expert system is a little odd, but since the system is a constant method based on know-how and experience of the expert in parameter adjustment, the combination seems to be natural. On the other hand, improvement of precision controllability in the areas of high quality, saving of resources, saving of energy, etc., in /832 the actual operation field is required. Thus, the operator is

expected to have operational know-how and accurate judgement to maintain the optimum control state. However, expert operators have extensive responsibility and the responsible tasks are getting complex, so there are some cases in which the tuning of the PID parameter is not adequate.

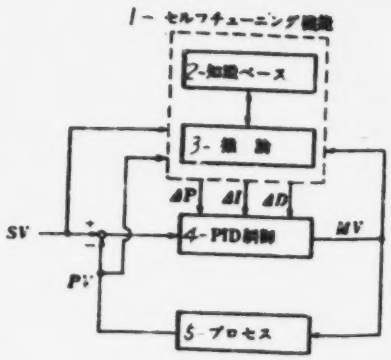

Figure 1. Block diagram of self-tuning function.

1--self-tuning function; 2--knowledge base; 3--inference; 4--PID control; 5--process

In summary, the purpose of the self-tuning (STC) is:

(1) Always maintain the best controllability following change in the dynamic characteristics of the controlled system.

(2) Reduce the tuning operation when the process is started up.

The strong points of the experts STC of NYS-80 are:

(1) Since it is self-tuning, it does not use the identification signal and threshold oscillation; thus, it does not disturb the process.

(2) The measuring signal is always observed; thus, the change in characteristics of the system can be detected quickly and the automatic self-tuning is executed.

(3) It does not require any special control theory.

(4) The setting parameters are few, consequently it is easy to use.

(5) There are both an update mode and a non-update mode (only calculation and identification of new parameters are executed) in the self-tuning and non-update mode. They act as a regular PID controller.

The operation principle of NYS-80 is as follows. The internal structure and the dynamic characteristics of many industrial processes are not analyzed enough, but they are comparatively stable. Even the PID parameter that is not at the optimum value can be controlled in its own way. There are four types as shown in

TABLE 1. Target type of control

	target	evaluation equation
0	no overshooting	zero overshooting
1	small overshooting 5%	$\min\int \lvert e \rvert \cdot t\,dt$ (ITAE)
2	medium overshooting 10%	$\min\int \lvert e \rvert dt$ (IAE)
3	large overshooting 15%	$\min\int e^2 dt$ (ISE)

e = control error

Table 1. In general, overshooting is not desired for heat treatment. For pressure and flow rate control, quick response is a higher priority and some overshooting is allowed.

From the response pattern of the measuring signal, the PID control rule to be applied is selected. The controller has more than 100 control rules and the optimum rule is selected from the response pattern or the transition tendency of the pattern. Figure 2 shows the basic patterns. For instance, in the case that the measuring signal is recognized as A pattern, the control rule which reduces both P and I is selected. Similar to the above, there are control rules for B, C and D patterns. Also, the control rule for the pattern which does not belong to the basic pattern is provided. As a part of the control rule, change of PID is obtained by the following equation. From the parameters of the present P, I and D, plus damping, overshooting and oscillation period of the response pattern, the next parameters are calculated.

$$PB_{N+1} = f_1(DMP, OVR, OSC) * PB_N \quad (1)$$
$$TI_{N+1} = f_2(DMP, OVR, OSC) * TI_N \quad (2)$$
$$TD_{N+1} = f_3(DMP, OVR, OSC) * TD_N \quad (3)$$

where PB: proportional band, TI: integral action time, TD: derivative time, DMP: damping, OVR: overshooting, OSC: oscillation period, subscript N: present value, subscript N+L: next value.

Now, the operation flow of the STC controller can be explained as follows (Figure 3): (1) In the case that the operation mode is automatic or cascade, go to STC mode. (2) When the control error exceeds the STC starting threshold value, observation of the measuring signal waveform is started. If the deviation is less than the threshold value, it is judged that the control is good. (3) For judgement of controllability, the consistency of the measuring signal waveform and the tuning target waveform is judged; i.e., in the case that the measuring signal waveform satisfies the overshooting and damping of the target without regard to the magnitude of control error, it is judged as the optimal tuning. If this does not satisfy, optimal tuning is calculated. (4) Finally, the necessity of update of the PID parameter is designated. In the case of no-update, only indication of the new parameter is executed.

These operations are executed with time sharing by the control period of the controller.

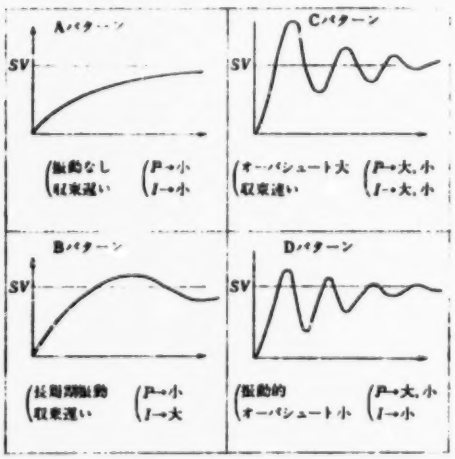

FIGURE 2. Basic response pattern. 1--start; 2--operation mode; 3--deviation; 4--observation of measuring signal waveform; 5--controllability; 6--calculation of PID parameter; 7--self-tuning; 8--PID diameter change; 9--PID control; 10--return; 11--startup process; 12--new PID indication only; 13--manual operation; 14--startup; 15--(control:good); 16--DB:Deviation set point for STC starting

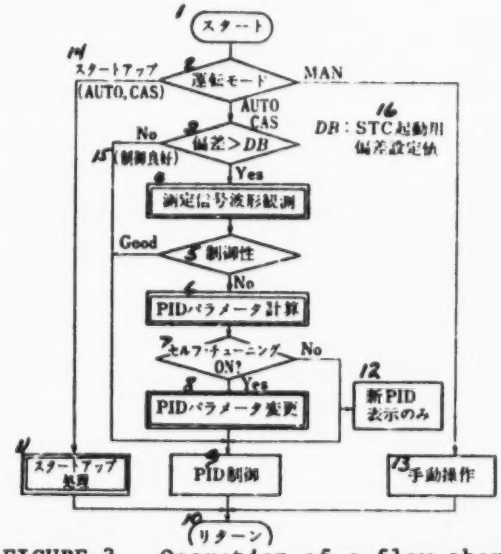

FIGURE 3. Operation of a flow chart of STC. 1--start; 2--operation mode; 3--deviation; 4--observation of measuring signal waveform; 5--controllability; 6--calculation of PID parameter; 7--self-tuning; 8--PID diameter change; 9--PID control; 10--return; 11--startup process; 12--new PID indication only; 13--manual operation; 14--startup; 15--(control:good); 16--DB:Deviation set point for STC starting

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Next, a application example of the STC is described. Many industrial processes can be approximated with a combination of the higher order lag element, dead time and gain.

$$G_p(s)=K\cdot\frac{e^{-Ls}}{(1+T_1s)(1+T_2s)\cdots(1+T_ns)} \quad (4)$$

For the change of gain which occurs by load change, disturbance and operating condition change, lag time constant and dead time, the method shows good tuning characteristics. The ratio of dead time and lag time (L/T) is recognized up to 5. Figure 4 shows an example of the STC started by setting value change for the controlled system including the first-order lag and the dead time. (T = 10 seconds, L = 10 seconds, K = 1). Zero overshooting was set as the control target. With the initial values of the proportional band 160%, the integral time 5 seconds, the derivative action time 0 seconds, it almost converges to the target pattern in 5 time trials. The final values of the parameters were the proportional band 104%, the integral time 18 seconds and the deviation time 3.5 seconds.

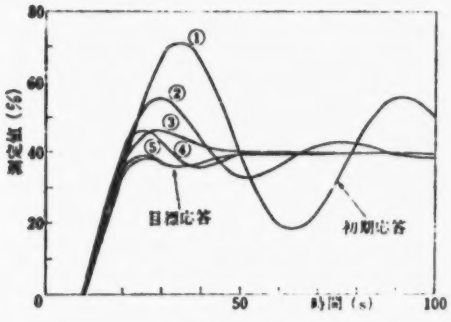

Figure 4. Self-tuning response waveform. 1--measured value (%); 2--time(s); 3--target response; 4--initial response

2.2 Auto-tuning by interactive operation

An auto-tuning controller which emphasizes the CAD method, New-MICREX (references 6 to 8), which is the revised version of the distributed digital process control system (MICREX-P) by Fuji Electric Co., is described in this paragraph. The threshold sensing method and the step response method can be pointed out as the methods which the control theory can apply to practical control. But the threshold sensing method is riskier because it increases the gain until its process becomes the oscillation mode. On the other hand, the step response method requires applying disturbance to the process for a long time to

obtain the step response, and in the case of a process with noise, it is difficult to sample process characteristics. Therefore, both of the methods are rarely used in practice. In practical control, the method in which the value is adjusted by observing the result of the control by setting the value to the safe side of PID is taken, and in this case the control is operated by trial and error thus (1) it requires time for the control operation, (2) the control results vary by operator, (3) due to time limits, the control stops and leaves room for improvement.

To solve these problems, the system has made possible the setting of the standard PID parameter by operating a button to utilize data storage accumulation and sophisticated arithmetic capability which are characteristic of the digital system. The main components of New-MICREX are as follows.

(1) Optimization method

new method was developed from the concept of the threshold sending method which was used in the base. With this method, good results are obtained by PI control in the region where the former method cannot be applied.

(2) Controlling operation

The use of auto-tuning implies eventual complete automatic optimal control. Since realization of auto-tuning is difficult with present theory, optimal controlled values are obtained according to the instruction of the operator and the results are indicated.

(3) Control mode

It is executed by the open-loop method but in the case that there is already some controlled values for the controlled parameter and there is a past operation, record with an open-loop, it is not necessary to be aware of the open-loop, i.e., even during execution

of the auto-tuning, the deviation of the process is monitored and when it is judged as abnormal, the control mode can be changed to a closed loop.

(4) Test signal /835

To check the characteristics of the process, the pulse test signal is input. This signal causes a disturbance in the operation so it is necessary to investigate the magnitude of this signal during regular operation. But during the test period of the plant, the signal can fall within tolerance limits.

(5) Check for reliability

Since a unique test signal is used, response of the process which is normal or not can be judged automatically in some degree. Also, the standard is to repeat the auto-tuning four times; thus the reliability of the results can be judged in comparison to the obtained results.

(6) Simulation

Points of view on the optimal control results vary. Since the standard optimal value is obtained in the system, it is effective to control for the individual requirement by observing the control simulation results indicated on the CRT screen.

Figure 5 shows the system composition of the distributed digital process control system, New MICREX. At the CRT operator station, two types of screens are provided to execute auto-tuning.

(1) Tuning panel

The tuning panel is the panel to obtain the optimal PID parameter by obtaining the process characteristics. The magnitude of the pulse for collection of the response and the various tuning conditions are set up. They command execution of auto-tuning

against the process station. The change of the process state during execution of the tuning is observed with a real-time trend indicator at the center of the tuning panel. When collection of data is completed, optimal control results are indicated.

(2) Simulation panel

With the results of the auto-tuning, the step response of the control results is simulated. Since the characteristic values of the process and the PID parameters can be changed on the screen, control can be accomplished on the CRT screen without operating the actual process. Because of the capability of the control which uses only the function of the simulation panel without collecting the pulse response, various applications, such as training, can be considered. As an application example of New-MICREX, the case of the loop which controls the supply of material by operating the motor speed of the conveyor is shown. Figure 6 shows the execution results of auto-tuning. This case is used for the on-site control of the plant and to check the reliability of the results. The auto-tuning was executed twice. Examples of the results are:

first pass: P_b = 145%, T_i = 31.9 seconds, T_d = 7.9 seconds

second pass: P_b = 158%, T_i = 30.0 seconds, T_d = 7.5 seconds

Since the difference of the results of the auto-tunings is small, it was decided that auto-tuning is reliable and it was set up for practical use.

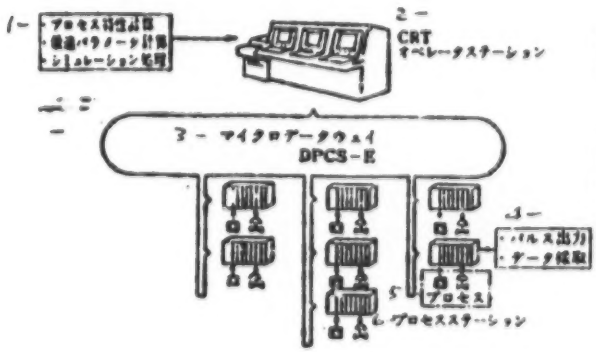

Figure 5. Composition of auto-tuning system
1--process characteristics calculation; optimal parameter calculation; simulation process; 2--CRT operator station; 3--microdata way DPCS-E; 4--pulse output; data collection; 5--process; 6--process station

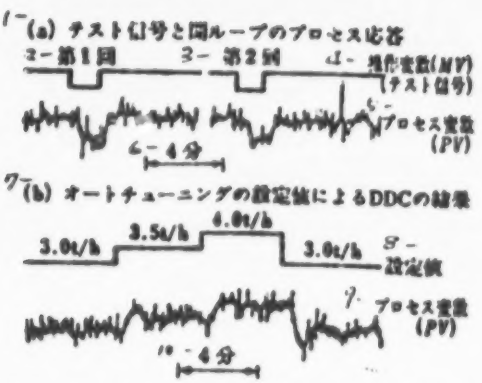

Figure 6. Execution results of auto-tuning
1--(a) test signal and process response of open loop; 2--first pass; 3--second pass; 4--operating variable (MV); 5--test signal; process variable (PV); 6--4 minutes; 7--(b) results of DDC with the setting values of auto-tuning; 8--setting value; 9--process variable (PV); 10--4 minutes

3. Auto-tuning of the real system

An individual method using the characteristics of the system is taken for tuning for real use. The following describes the tuning method of an actual system.

3.1 Interactive on-line tuning system of BWR plant control system

To shorten the control period of a BWR nuclear plant, Toshiba Corp. developed a control system design method [15] by the on-line identification method and partial model matching [1,2]. The tuning guide system was prepared with the personal computer base. It is composed of identification of the controlled system by the AR model and conversion to the continuous system; design of proportion/integration parameters by the model matching method; simulation of the closed-loop response of the combination of the above; and the evaluation function of the response waveform. The control system /836
was to be adjusted has to be adjusted to meet the demand to make changes of the control input small and to ensure quick response of the controlled variable. Thus, tuning adopting the requirement to adjust with interaction is possible. Figure 7 shows the composition of the recirculation system and the measurement signal. In the recirculation flow control system, it is necessary to control the

speed of the pump so that the response waveform of neutron flux and main stream flow meet specifications. Also, to identify the non-linear property of the characteristics to the plant, it is necessary to have the gain schedule of the control constant.

From the test data of the step response, the transfer function is approximated by the method of least squares and the conversion method to the continuous system. Then from the simulation used above, the response of the speed of the pump, the neutron flux, the main stream flow and the modeling of the system are executed.

The partial model matching method is used for tuning. The control constant is determined from the relationships between the response time constant, which prescribes the response of the reference model and the response characteristics of the control system designed from the results of the response time constant. Compared with optimization methods of the past, the control constant which meets various control requirements simultaneously can be obtained with a simple algorithm.

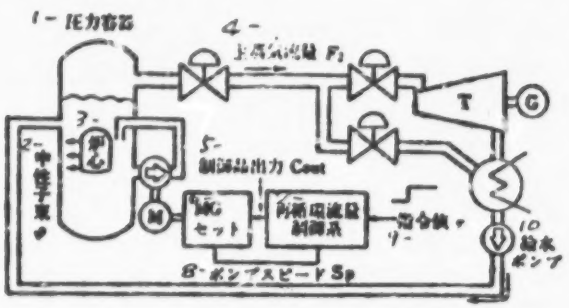

Figure 7. Composition of recirculation system and measurement signal
1--pressure vessel; 2--neutron flux; 3--reactor core; 4--main flow; 5--controlled output; 6--MG set; 7--recirculation flow control system; 8--pump speed; 9--command value; 10--feed pump

3.2 Auto-tuning of dissolved oxygen concentration control for sewage

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Control of the dissolved oxygen concentration (DO) in the aeration vessel at a sewage treatment plant directly connected to the blower which stabilizes the quality of the treated water and consumes large amounts of plant power (control is important also from the standpoint of power saving). It is known that the DO process is operated stably by setting the proper control parameter by the PI control method. However, there is a problem in that it is difficult to maintain good control due to changes in characteristics by process state. For the DO process in the aeration vessel, if the residence time is assumed to be long enough, the following equation depicts a well known model with air quantity u(m^3/h) and DO x(ppm).

$$\frac{dx}{dt} = an^{n}(x_0 - x) - R_r + v \qquad (8)$$

where a and n are the constants of the plant. $\bar{x}_0$ is the saturation DO (ppm) at the water temperature θ(C°), R_r is the oxygen respiration speed (ppm/h) and v is disturbance. It is known that R_r and v are affected by various factors such as load by water temperature, quantity and quality of the inflow sewage and concentration of activated sludge.

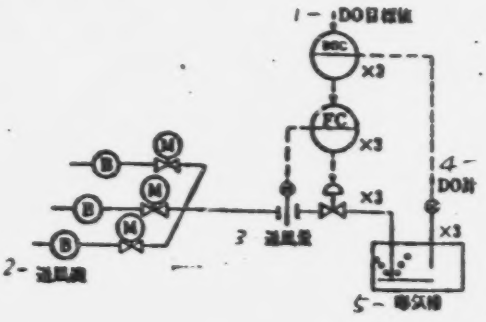

Figure 8. Composition of DO control system.
1--DO command; 2--blower; 3--quantity of air blast; 4--DO meter; 5--aeration vessel

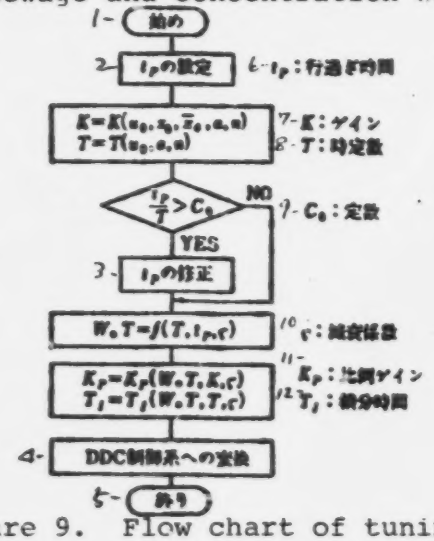

Figure 9. Flow chart of tuning.
1--start; 2--setting of t_p; 3--correction of t_p; 4--conversion to DDC control system; 5--finish; 6--t_p: overshoot time; 7--K: gain; 8-- T--time constant; 9--C_0: constant; 10--ζ: damping coefficient; 11--K_p--proportional gain; 12--T_I: integral action time

For this system, the gain schedule type auto-tuning method is applied. Calculation procedures are as follows:

(1) By making linear the nonlinear model of the controlled system near the equilibrium point, it is formulated as a first order lag and the parameter of the first order lag is operated from various values of the process.

(2) From the operated parameters of the first order lag, the PI control parameter which meets the following design guide is determined.

a) the damping coefficient ζ is constant;

b) the overshoot time t_p of the step response is constant; /837

c) reduce the steady-state deviation and design to balance quick response and stability.

Figure 8 shows the composition of the DO control system and Figure 9 shows the flow chart of the tuning.

3.3 Excitation control of earthquake simulation

To check if nuclear power plants, buildings and chemical plants have sufficient strength to withstand earthquakes, the earthquake-proof strength test is performed. The purpose of the earthquake simulator [17,18] is to test vibration characteristics by stressing the actual structure or its model under a state similar to earthquake. For the earthquake simulator, realization of the following items are as important as the characteristics of the control system.

(1) The characteristics are hardly affected by the test object or effects can be compensated.

(2) The earthquake wave or the random wave recorded with the acceleration wave can be regenerated accurately.

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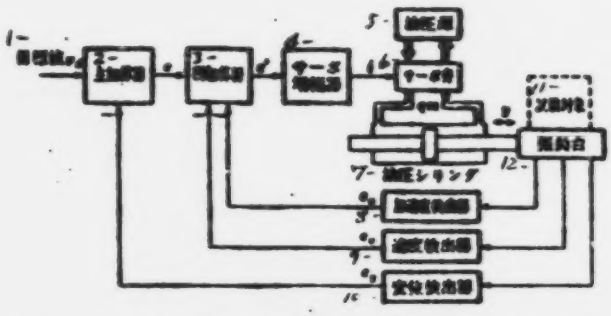

Figure 10. Basic composition of earthquake simulator.
1--command; 2--main adder; 3--auxiliary adder; 4--servo amplifier; 5--hydraulics source; 6--servo valve; 7--hydraulic cylinder; 8--acceleration detector; 9--velocity detector; 10--displacement detector; 11--test object; 12--shaking table

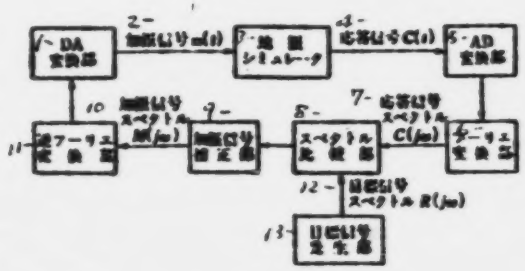

Figure 11. Composition of learning control system.
1--DA converter; 2--excitation signal m(t); 3--earthquake simulator; 4--response signal C(t); 5--AD converter; 6--Fourier transformer; 7--response signal spectrum C(jω); 8--spectrum comparing component; 9--excitation signal correction component; 10--excitation signal spectrum m(jω); 11--inverted Fourier transformer; 12--command signal spectrum R(jω); 13--command signal generation component

The basic composition of the simulator is shown in Figure 10. The control system is set up so that the displacement y of the shaking table follows the target value v_d. The earthquake simulator has complex transfer characteristics. The effects of the nonlinear property is significant. To correct these characteristics, it is necessary to identify the transfer characteristics of the earthquake simulator as accurately as possible and to improve accuracy of the response waveform. Thus, the method has to be adopted in which the correction of the excitation signal is repeated so that it converges within the tolerance of the accuracy. The composition of the learning control system which realizes the above function is shown in Figure 11. When r(t), R(jω) are the command signals,

$m_i(t)$, $M_i(j\omega)$ are the excitation signal at no. i, $C_i(t)$, $C_i(j\omega)$ are the response signals of the earthquake simulator for no. i excitation signal, $G(j\omega)$ are the transfer function, No. i + 1 excitation signal $m_{i+1}(t)$ uses the signal of the inverse Fourier transform of equation (6).

$$M_{i+1}(j\omega) = M_i(j\omega) + G^{-1}(j\omega)\{R(j\omega) - C_i(j\omega)\} \tag{6}$$

By executing repetitions of the correction of equation (6), the transfer characteristics and the response waveform distortion of the earthquake simulator can be corrected.

4. Algorithm of tuning

4.1 Identification of plant dynamic characteristics

The z transfer characteristics of the controlled system through the zeroth-order hold are expressed in equation (7).

$$y(n) = \frac{N(z^{-1})}{D(z^{-1})}u(n) = \frac{b_1 z^{-1} + b_2 z^{-2} + \cdots}{1 + a_1 z^{-1} + a_2 z^{-2} + \cdots}u(n)$$
$$= G_p(z^{-1})u(n) \tag{7}$$
$$y(n) = \theta^T \Phi(n) \tag{8}$$

Equation (7) is rewritten as equation (8). In the equation,

$$\theta^T = (a_1, a_2, \cdots, b_1 \cdots b_2),\ \Phi^T(n) = [-y(n-1), -y(n-2), \cdots, u(n-1), u(n-2), \cdots]$$

From the above, the estimate of $\hat{\theta}(n)$ of θ is obtained from the algorithm of the following equations:

$$\hat{\theta}(n) = \hat{\theta}(n-1) + k(n)\{y(n) - \hat{\theta}^T(n-1)\Phi(n)\} \tag{9}$$

$$k(n) = \frac{\Gamma(n-1)\Phi(n)}{1 + \Phi^T(n)\Gamma(n-1)\Phi(n)} \tag{10}$$

$$\Gamma(n) = \{I - k(n)\Phi^T(n)\}\Gamma(n-1),$$
$$\hat{\theta}(0) = 0,\ \Gamma(0) = \alpha I > 0 \tag{11}$$

Since the algorithm is

$$T_r(\Gamma(n)) - T_r(\Gamma(n-1))$$
$$= -(1 + \Phi^T(n)\Gamma(n-1)\Phi(n))^{-1} \cdot \|\Gamma(n-1)\Phi(n)\|^2 \leq 0 \tag{12}$$

$\Gamma(n)$ easily causes the underflow and continuation of the algorithm is sometimes difficult. To avoid this problem, reset of the initial value of $\Gamma(n)$ is considered. As a better method, using the fixed trace gain algorithm with the generalized adaptive rules by Landau [18] is adequate.

When

$$\varepsilon(n)=(\hat{\theta}(n)-\theta)^T\Phi(n)=\zeta^T(n)\Phi(n) \tag{13}$$

the following equations can be obtained:

$$\hat{\theta}(n)=\hat{\theta}(n-1)-\Gamma(n-1)\zeta(n)\varepsilon(n) \tag{14}$$

$$\Gamma(n)=\frac{1}{\lambda_1(n)}\left[\Gamma(n-1)-\frac{\Gamma(n-1)\zeta(n)\zeta^T(n)\Gamma(n-1)}{\mu+\zeta^T(n)\Gamma(n-1)\zeta(n)}\right] \tag{15}$$

$$\lambda_1(n)=1-\frac{\|\Gamma(n-1)\zeta(n)\|^2}{(\mu+\zeta^T(n)\Gamma(n-1)\zeta(n))\,T_r(\Gamma(n))},\qquad \mu>0.5 \tag{16}$$

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In this case, underflow does not occur and $\Gamma(n)$ is bounded at $T_r(\Gamma(n))=T_r(\Gamma(0))=\alpha I>0$.

To convert from $G_p(z^{-1})$ to the transfer function G(s) in the S region, $z^{-1}=e^{-\tau s}$ (τ is the sampling period) is executed by MacLaurin's expansion, paying attention to equation (17) and the coefficients are compared.

$$Z[G_H(s)G(s)]=G_p(z^{-1}),\quad G_H(s)=\frac{1-e^{-\tau s}}{s} \tag{17}$$

Then the denominator serial expansion of G(s) is obtained by the following a algorithms

$$G_p(z^{-1})=\frac{\sum_{k=1}^{\infty}b_k(z^{-1})^k}{1+\sum_{k=1}^{\infty}a_k(z^{-1})^k}\rightarrow G(s)=\frac{1}{\sum_{k=0}^{\infty}G_kS^k} \tag{18}$$

$$A_0=1+\Sigma a_i,\quad A_k=\frac{(-\tau)^k}{k!}\Sigma i^k a_i\ (k\geq 1)$$

$$B_k=\frac{(-\tau)^k}{k!}\Sigma i^k b_i\ (k\geq 0) \tag{19}$$

$$H_0=A_0/B_0,\quad H_k=\left(A_k-\sum_{r=0}^{k-1}H_rB_{k-r}\right)\Big/B_0\ (k\geq 1)$$

$$G_0=H_0,\quad G_k=\left(H_k-\sum_{r=1}^{k}\frac{\tau^r}{(r+1)!}G_{k-r}\right)\ (k\geq 1) \tag{20}$$

4.2 Determination of PID parameter

In the past, the step response method of Ziegler-Nichols and the threshold sensing method [21] have been used. However, adopting the step response by tuning involves considerable cost and time; thus, the practical system is limited. Occurrence of the self-excited vibration in the controlled system risks system failure. The method which is now used often is the partial model matching method [1-3] that Kitamori proposed.

When the PID controller is expressed as equation (21), the closed loop system W(s) is expressed as equation (22).

$$G_c(s)=K_p\left(1+\frac{1}{T_i s}+T_d s\right) \tag{21}$$

$$W(s)=\frac{G_c(s)G_p(s)}{1+G_c(s)G_p(s)},\quad G_p(s)=\frac{1}{\sum_{k=0}^{\infty} G_k s^k} \tag{22}$$

The norm model transfer function $W_m(s)$ of W(s) is given by equation (23).

$$W_m(s)=\frac{1}{\sum_{k=0}^{\infty} \alpha_k \sigma^k s^k} \tag{23}$$

Kitamori proposed equation (24) for the serial α_i in which a good controllability waveform is obtained with 10% overshoot.

$$\alpha=(\alpha_0, \alpha_1, \cdots)=(1, 1, 0.5, 0.15, 0.03, \cdots) \tag{24}$$

To make W(s) close to W_m (s), it is assumed W(s) = W_m(s) and K_p, T_i, T_d and σ are obtained from comparison of coefficients from the lower order of s. For the PI control with α_0 = 1

$$(\alpha_2^2-\alpha_1\alpha_3)G_0\sigma^2-\alpha_1\alpha_2 G_1\sigma+\alpha_1^2 G_2=0 \tag{25}$$

The minimum root at $\sigma > 0$ is obtained from equation (26).

$$\begin{aligned}&(\alpha_2^3-2\alpha_1\alpha_2\alpha_3+\alpha_1^2\alpha_4)G_0\sigma^3+\alpha_1(\alpha_1\alpha_3-\alpha_2^2)G_1\sigma^2\\&+\alpha_1^2\alpha_2 G_2\sigma-G_3\alpha_1^3=0\end{aligned} \tag{26}$$

AC this time, the PID parameters are as follows:

$$\begin{aligned}&K_p=\frac{\alpha_1 G_1-\alpha_2 G_0\sigma}{\alpha_1^2\sigma},\quad T_i=\frac{\alpha_1 G_1-\alpha_2 G_0\sigma}{\alpha_1 G_0},\\&T_d=\frac{(\alpha_2^2-\alpha_1\alpha_3)G_0\sigma^2-\alpha_1\alpha_2 G_1\sigma+\alpha_1^2 G_2}{\alpha_1(\alpha_1 G_1-\alpha_2 G_0\sigma)}\end{aligned} \tag{27}$$

5. Conclusions

The trend of today's tuning is changing from the off-line type of Ziegler-Nichols to the on-line. This is from development of the microprocessor and introduction of the CAD method. It seems that these trends continue. However, we are still far away from complete auto-tuning. For the control in actual use, the control method which can be reliable experimentally is desirable because of the important of reliability. The aim of a reliable control method would be having lower limits. Thus, even though the model norm type adaptive control and STR [22] of Astrom and Ljung are theoretically explicit, applications are few. For instance, 1) the composition of the controlled system is limited; 2) the order of the system has to be known; 3) the numerator has to be stable; 4) the identification signal has to be PE (persistently exciting). The direction of theoretical control has removed these limits one by one and it is necessary to examine the control in actual use. At the same time there are many problems in the controls in real situations. For instance, 1) assurance of stability [24]; 2) expansion for multivariables and these problems should be studied in theoretical control as a matter of course, but they are not. The magnitude of the gap between theory and practice depends on the people concerned with theoretical control and control in actual use. This report does not cover all aspects of tuning, but only some. There are some cases [4,5] that use interesting methods, but they were omitted due to space limitations in this report. Finally, the authors cordially thank Professor Toshiyuki Kitabayashi of the Engineering Department of Tokyo University, Tadamichi Kai of Yokokawa Hokushin Electric Co., Tokuji Ota of Fuji FACOM Control, Ryuichi Kuwata of Toshiba Corp., and Masaya Tanuma of the Hitachi Co. for supplying data.

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